Navy Electronics Laboratory
Report 1165

SLOTTED-RIDGE WAVE GUIDE PLANAR ARRAYS, by J. H. Provencher and W. W. Grant. 29 p., 24 April 1963.

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1. Slot antennas
2. Wave guides - Electromagnetic properties

I. Provencher, J. H.
II. Grant, W. W.

AD 01401
SF 001 02 05, Task 6072
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  CHIEF, ELECTRONICS DIVISION

THE PROBLEM

Investigate and develop new antenna techniques for shipborne air-search radar applications. Specifically, this report deals with one phase of the development of antenna arrays for radar search and other uses.

RESULTS

1. Standard rectangular wave guides, loaded by the use of a ridge, were used to make parallel-slot antenna arrays, capable of being scanned $\pm 45°$ off the broadside position.

2. Rigid coaxial transmission line distribution systems were studied, in respect to phase shift, for possible use as a suitable distribution system for a phase-scanned array.

3. The dual-ridge wave guide array is proposed as a means of using the same aperture for multiple-frequency bands. Preliminary data on dual-ridge wavelengths are given.

RECOMMENDATIONS

1. Determine fully the advantages to be gained by the use of a phase-scanned array, when the state of the art produces a low-loss, high-speed, phase-shifting technique.

2. Investigate further the characteristics of the dual-ridge wave guide, with a view to using them as elements in

a multifrequency array. This would allow use of the same aperture area for more than one radar (thus providing frequency diversity) or for more than one function, such as in search and guidance.

3. Determine to what extent the frequency band of the fixed-aperture scanning antenna can be extended, utilizing time-delay or variable-path-length beam steering, and broadband tee dividers for amplitude control.

ADMINISTRATIVE INFORMATION

Work was performed under SF 001 02 05, Task 6072 (NEL D1-17), as assigned by BUSHIPS letter ser 362-033 of 5 April 1962, by members of the Radar Division.

The report covers work from January 1961 to July 1962, and was approved for publication 24 April 1963.

CONTENTS

ILLUSTRATIONS

INTRODUCTION

In the design of antennas for low-frequency radar, the achievement of the increasingly large apertures which are required is limited, in the conventional antenna, by the need for large rotating mechanical mount systems. The fixed-aperture scanning antenna offers one solution but, in the case of the time-delay or phase-shift scanning array, presents the problem of mutual coupling and impedance effects between individual elements.

For the infinite planar array the mutual effects involve only the gain of the array, which might be disregarded. In a finite array, however, the mutual coupling between the elements is a variable across the aperture, the greatest variation being produced by the elements at the ends of the array[1] (see list of references at end of report). Thus the aperture distribution, being a function of the impedance, will vary with scan angle. These conditions combine to give a progressive pattern deterioration as the beam is scanned off the broadside position. The degree of pattern deterioration is more pronounced in arrays with a relatively small number of elements.

The beam is scanned by some method of introducing a phase shift in equal increments between elements. This may be done by various means, such as mechanical or electrical phase shifter, or by the use of rotating mechanisms, line stretchers, or ferrite devices. Analytically, the field (fig. 1) is given by [2]

$$E(\theta) = A_0 + A_1 \exp(j\psi) + A_2 \exp(2j\psi) \ldots A_n \exp(nj\psi)$$

where θ is the beam pointing angle off broadside, A_n is the amplitude of the feeding current, and ψ is defined as

$$(2\pi/\lambda)\, d \sin\theta - \delta$$

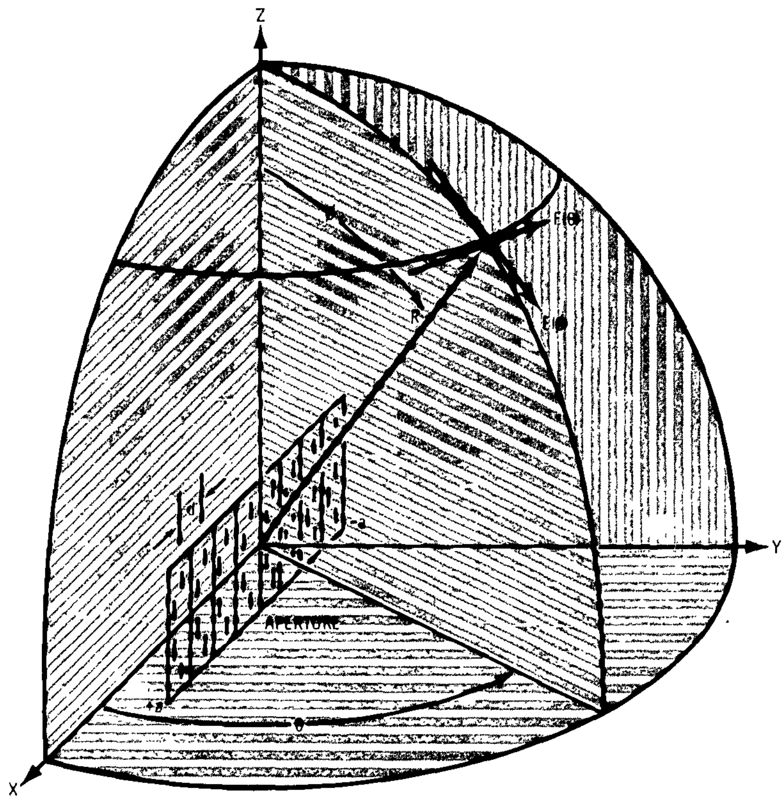

Figure 1. Sketch of array coordinate system.

where δ (radians) is the phase increment between elements, λ is the free-space wavelength, and d is the element spacing in wavelengths.

A source of error in the array is the feeding harness or network required to provide the proper amplitude and phase distribution at the element terminals. Several approaches are possible, such as the corporate feed structure, the slotted wave-guide feed, and the pillbox type of power divider. The corporate type structure was chosen because of its high power capability and its relative simplicity. A computational study made of a 16-terminal harness designed to provide a -40 db Dolph-Tschebyscheff

(D. T.) distribution[3] and constant phase at the output terminals showed that the amplitude and phase distributions were highly frequency-sensitive (figs. 2, 3) and that their values were not acceptable for the chosen design goals (fig. 4). This study pointed up the need for a feed system which could maintain an acceptable amplitude and phase distribution over a relatively broad frequency band.

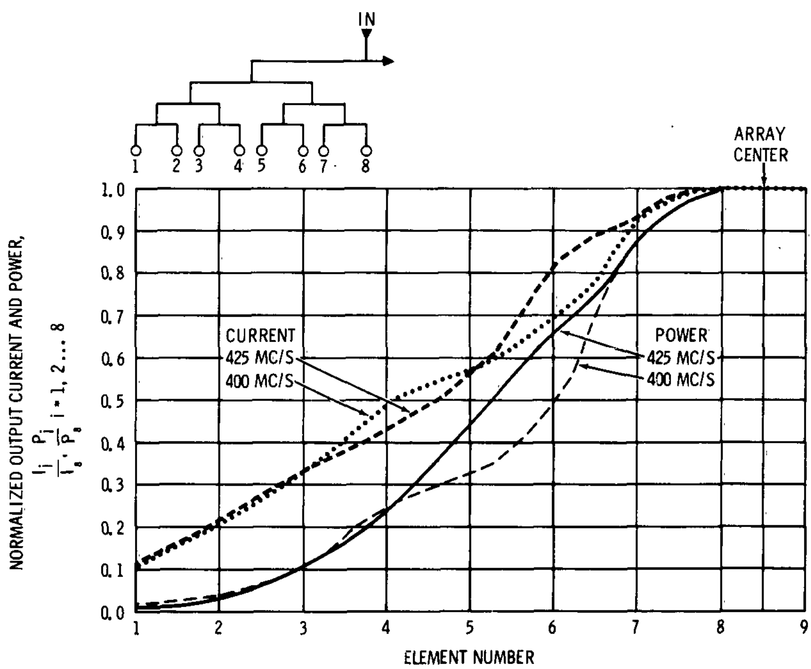

Figure 2. Current and power distributions vs. element number; 16-element D. T. array harness; -40 db side-lobe level at 425 Mc/s.

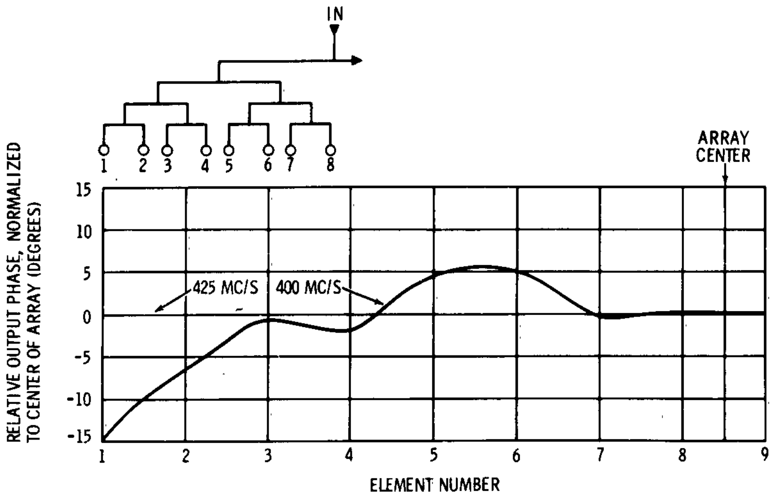

Figure 3. Relative phase vs. element number; 16-element D. T. array harness; -40 db side-lobe level at 425 Mc/s.

One approach to the over-all problem is to design the array elements so that the impedance at the input terminals is real, and then match each element in its array position to an "active impedance." This active impedance is the impedance of the element measured at the input terminals with induced currents flowing at the other element input terminals. From the impedance data thus obtained, the feed harness can then be designed. For arrays with a relatively large number of elements this might seem an insurmountable task. However, as the array becomes larger, the elements near the center essentially "see" the same environment and correspondingly the same impedance. As a result, experimental data need be taken only at the center elements if the array is large. The effects of errors produced by the end elements are considered negligible.

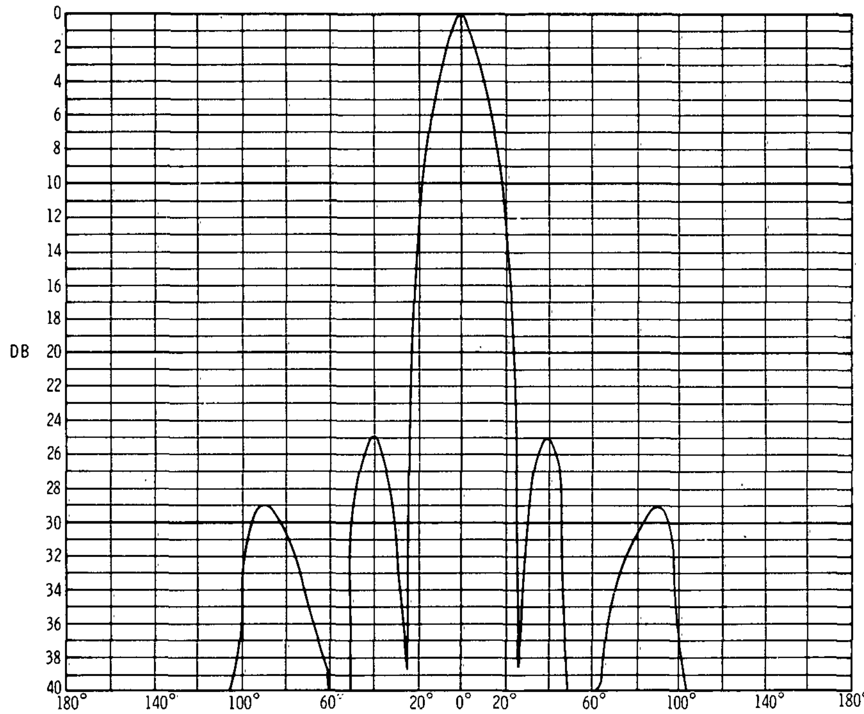

Figure 4. Calculated pattern at 400 Mc/s of a 16-element D. T. array whose corporate feed structure was designed at 425 Mc/s for -40 db side lobes.

THE EXPERIMENTAL ANTENNAS

Previous work resulted in the design and development of a suitable element for the arrays.[2] The element is a linear array of six longitudinal shunt slots in the broad face of a rectangular ridge wave guide, and was chosen for its approximately omnidirectional azimuth pattern and its rigidity. The planar array was to be horizontally polarized and operate in the 3.000 Gc/s region (S band), and would serve as a model for eventual uhf antennas for long-range search radar applications. The required beam width was about 22° in the vertical (H) plane. The element had a measured gain of about 11.8 db over an isotropic source at the design frequency of 3.040 Gc/s. Its input impedance was 50 ohms and the element was fed by a 7/8-inch rigid coaxial transmission line.

The desired scanning range was to be ± 45° off the broadside position ($\theta = 0$) and was to be achieved for the model antennas by the use of RG-9U coaxial cables precisely measured and cut to be within 2° of the phase difference required to point the beam in a chosen direction. These cables introduced a path length difference, but this was ignored because the frequency was not to be changed. For arrays of a few elements the cable technique of phase shifting can be desirable but, for the larger arrays, it becomes tedious as a different set of cables is required for every beam position desired, and in many cases is prohibitive in time and effort for the results achieved.

The feed harnesses were designed to have a real input impedance of 50 ohms and an output impedance of 50 ohms across each pair of element terminals. The phase distribution was to be constant to within 3°, a value believed to be necessary to maintain a desirable pattern at the broadside position. The amplitude distribution was chosen so as to place a -30 db Dolph-Tschebyscheff taper across the elements. This was achieved through the corporate structure by the use of quarter-wave transformers to give the proper power distributions at the various branch points. The harnesses were constructed from 7/8-inch rigid coaxial line with air dielectric.

RESULTS OF MEASUREMENTS

To study the effects of mutual coupling from the end elements on the radiation pattern, three arrays were built with three, six, and 12 elements respectively. The three-element array (1.5λ) was fed through tees chosen to place a -15 db D.T. taper across its terminals. In this case, the "end" effects were large, and the elements were matched to the active impedance of 50 ohms. The pattern showed -15 db side lobes as predicted; however, the minima did not go to zero, indicating phase errors. The pattern had a half-power beam width of 35°. No attempt was made to scan this array as the results would be of little significance (fig. 5).

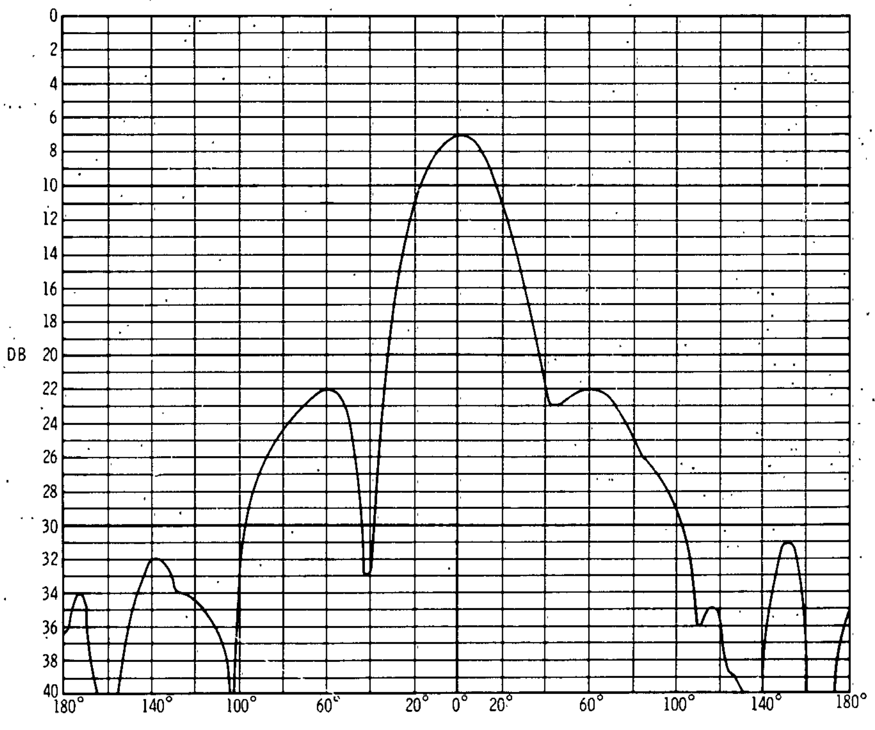

Figure 5. Radiation pattern of 18-slot planar array; f = 3.040 Gc/s; beam width, 35° at -3 db; θ = 0; δ = 0; gain ≈ 15 db.

The six-element, 36-slot array was designed to have a -30 db D. T. taper across its terminals. Each element was matched to an active impedance of 50 ohms. The array was fed by a corporate structure made of 7/8-inch rigid coaxial line. Phase measurements made at the harness output terminals showed a linear phase distribution within the 3° desired. Amplitude measurements indicated that the individual power amplitudes were within 0.5 db of the design values. The input VSWR was 1.08 at the design frequency. The phase measuring setup is shown in figure 6. The phase was measured through the harness and phase shifting cables, and in all cases the phase error was less than 2°.

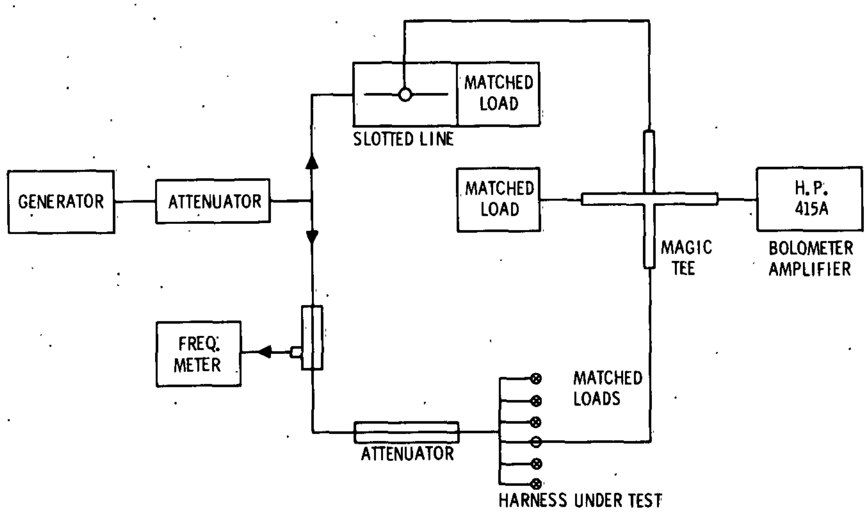

Figure 6. Diagram of phase measuring setup.

Radiation patterns of the 36-element array had a 24° beam width and -29 db side lobes at the broadside position, and a gain of 18.8 db. As the beam was scanned through various chosen angles, the beam width and the side-lobe level increased as expected: at 13.8° the side lobes were -26 db and the beam width 24°; at 28.3° the side lobes were -23.5 db and the beam width 27°; and at 41° the side lobes were -16 db and the beam width was now 31°. These patterns are shown in figures 7-10.

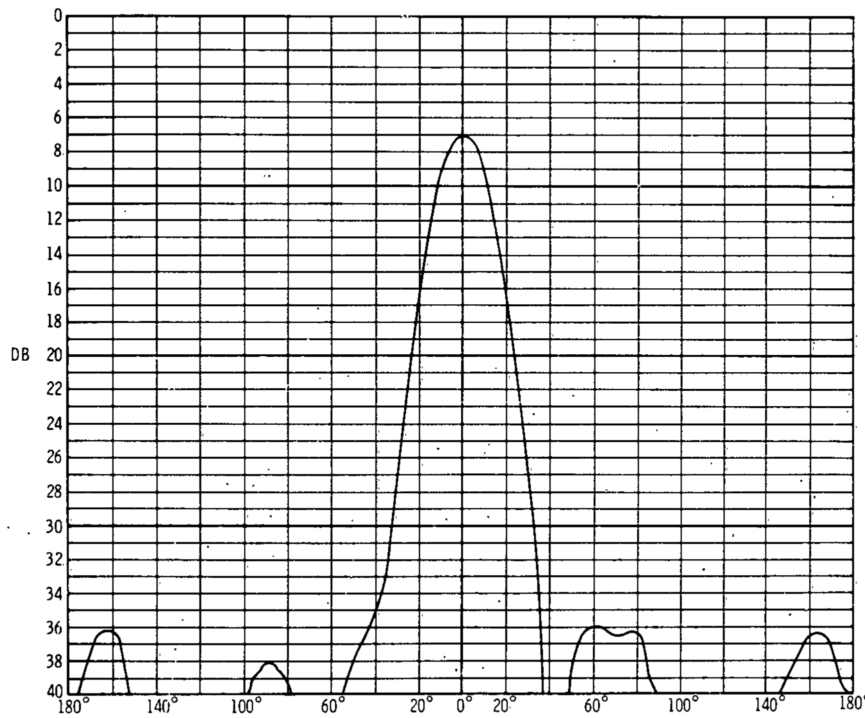

Figure 7. Radiation pattern of 36-slot planar array; f = 3.040 Gc/s; θ = 0; δ = 0; beam width, 24° at -3 db gain; gain, 18.8 db.

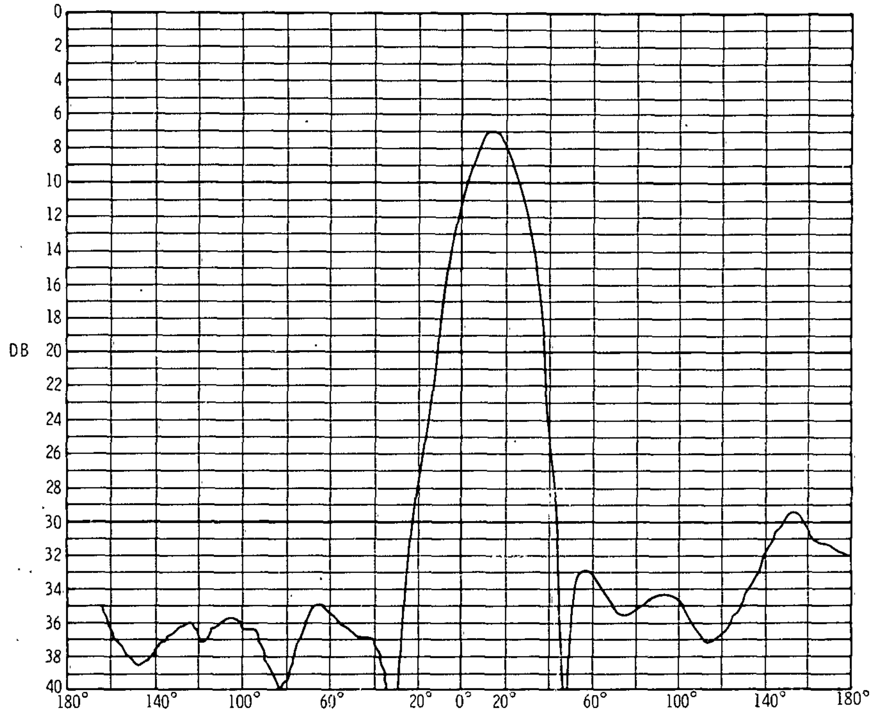

Figure 8. Radiation pattern of 36-slot planar array; f = 3.040 Gc/s; θ = 13.8°; δ = 43°; beam width, 24° at -3 db.

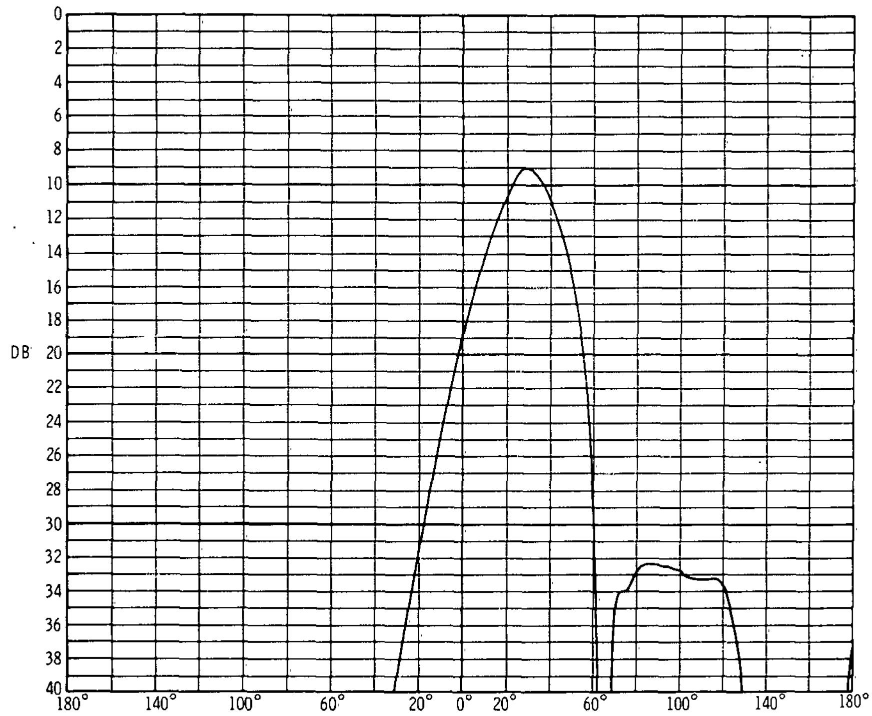

Figure 9. Radiation pattern of 36-slot planar array; f = 3.040 Gc/s; θ = 28.3°; δ = 85°; beam width, 27° at -3 db.

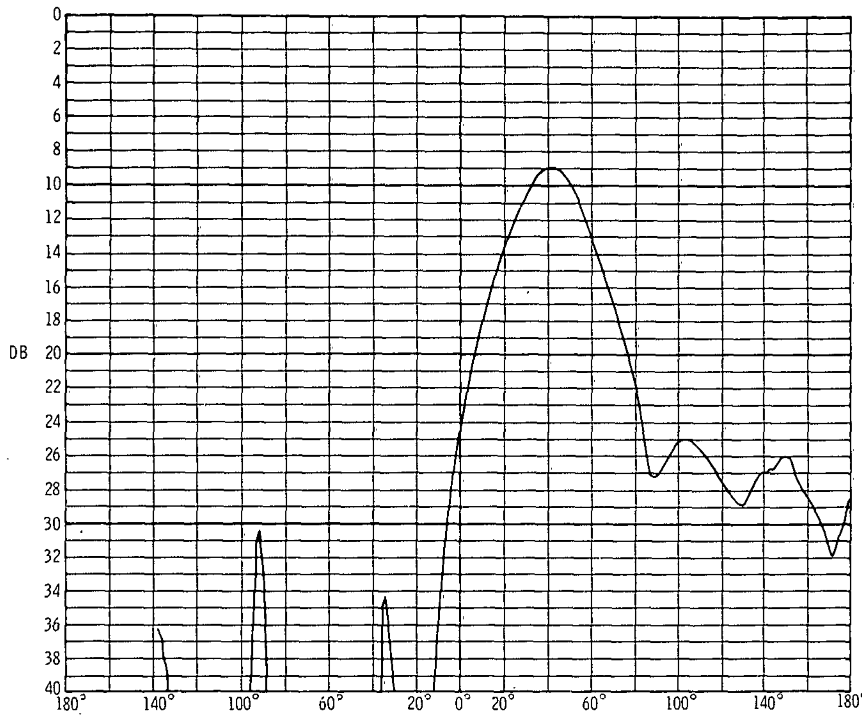

Figure 10. Radiation pattern of 36-slot planar array; f = 3.040 Gc/s; θ = 41.0°; δ = 118°; beam width, 31° at -3 db.

With the data gained from the 36-slot array model, a 72-slot, 12-element model was designed and built using the same basic element. The feed harness was again designed to give a -30 db side-lobe distribution and constant phase across the output terminals (fig. 11). The element input terminals were matched to an active impedance of 50 ohms. Phase measurements made on the feed harness showed that the 3° tolerance on the phase distribution was not held at two output terminals; this error, however, was corrected by changes in the flexible coaxial lines. The amplitude measurements showed that the element amplitudes were within the design tolerance. The broadside pattern of this array (fig. 12) yielded side lobes higher than predicted by the theoretical design (-25 db). In an attempt to account for the discrepancy, the pattern of each

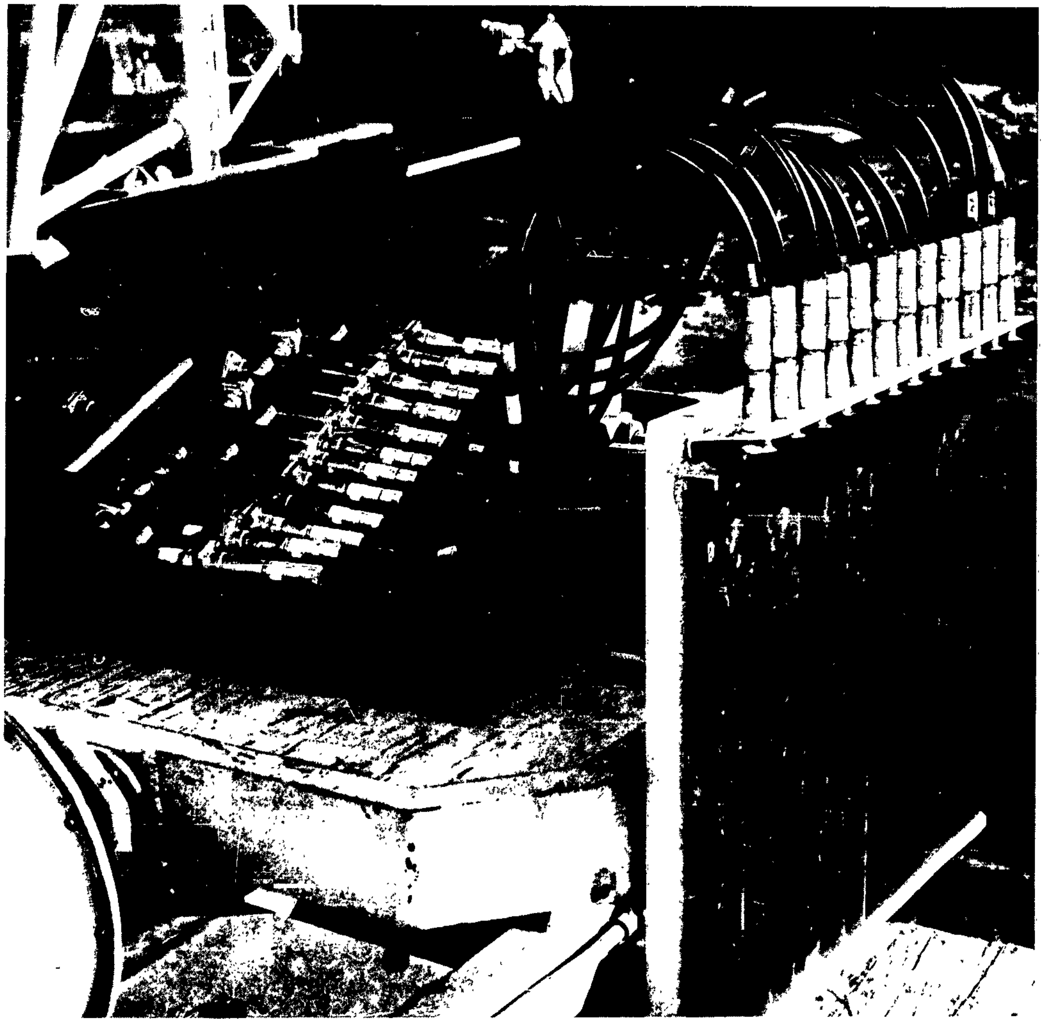

Figure 11. Photograph of 72-slot array with corporate feed structure.

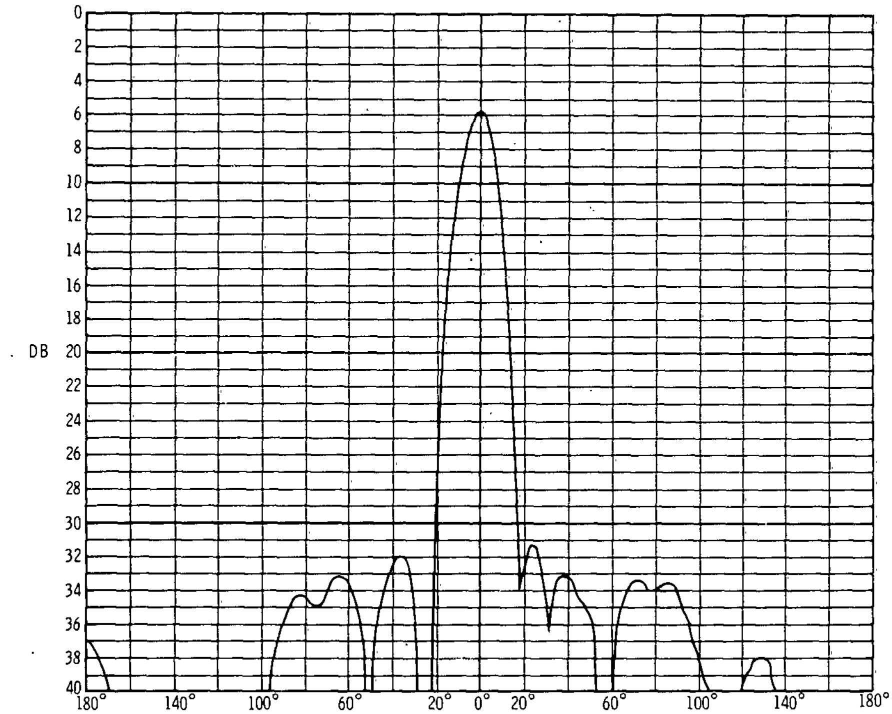

Figure 12. Radiation pattern of 72-slot planar array; $f = 3.040$ Gc/s; $\theta = 0$; $\delta = 0$; beam width, 15° at -3 db.

individual element, in its position in the array, was taken with all other elements terminated in matched loads. The variation of the patterns with array position is given in figure 13. Only six elements are plotted, as the other six are similar. There are variations not only in pattern shape but also in the amplitudes of the elements, which in some instances varied as much as 1 db. This error in amplitude, if coupled with the ± 0.5 db maximum tolerance error of the feed harness, could well account for the discrepancy in side-lobe level.

The 12-element array was not scanned because of the large number of cables which would be required for each scan angle desired. It was assumed, however, that the scanning characteristics (i.e., side-lobe level) would be improved over those of the 36-element array, since the effects of random errors decrease as the number of elements increases.[4]

In order to experimentally evaluate the effect of various phase tolerances on the radiation pattern, the array was fed with harnesses having phase tolerances of $\pm 5°$ and $\pm 8°$ on the phase distribution. For the $\pm 5°$ case, the side-lobe level rose about 3 db, and for the $\pm 8°$ case, the side-lobe level was increasingly higher, because of the previously mentioned effects. The beam shape of the over-all pattern did not appear to experience any radical changes at the broadside position. These patterns are shown in figures 14 and 15.

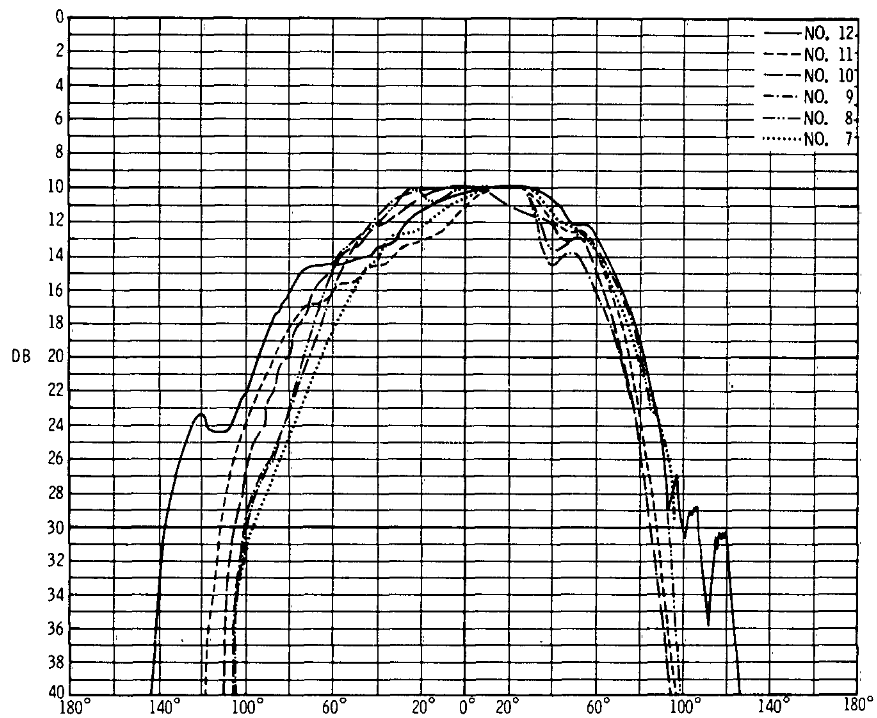

Figure 13. Radiation pattern of 72-slot planar array, showing variation of element pattern as a function of position in array; f = 3.040 Gc/s.

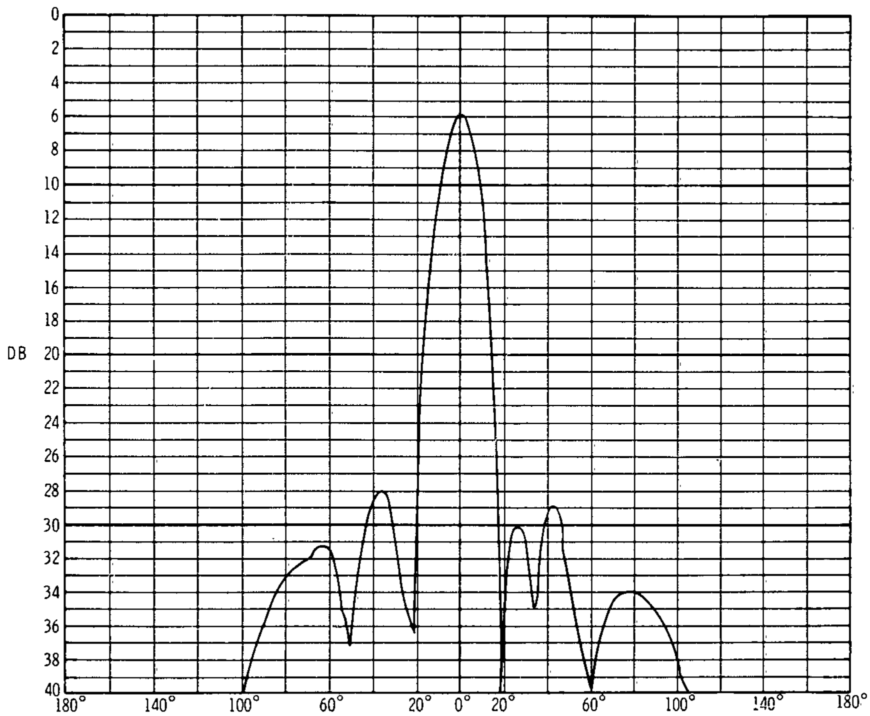

Figure 14. Radiation pattern of 72-slot planar array; f = 3.040 Gc/s; θ = 0; phase tolerance, ± 5°.

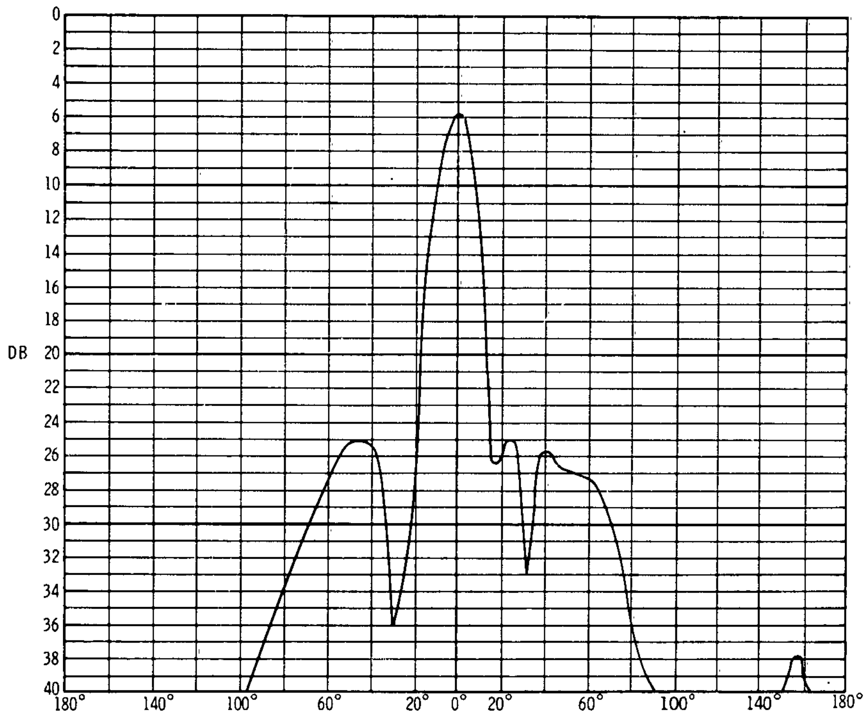

Figure 15. Radiation pattern of 72-slot planar array; f = 3.040 Gc/s; θ = 0; phase tolerance, ± 8°.

POWER DIVIDING NETWORK

The need for a network or harness which is capable of placing the proper amplitude and phase distributions across the input terminals of the array became increasingly evident as the frequency was changed. The results of the study were substantiated experimentally by phase and amplitude measurements. The discrepancies between theoretical and experimental values were more pronounced in the harness with 12 outputs, even though the element current ratios were not as great as with the six-element array. As the frequency is changed, the quarter-wave transformer becomes reactive, causing a phase shift proportional to the angle of the reflection coefficient. The need arises, therefore, for some method for keeping the angle of the reflection coefficient small enough to keep the accompanying phase shift within the design tolerances. In effect, this means broadbanding the transformers in a dividing tee with respect to small phase dispersion. This problem appears to be solved by a method devised by Keeping.[5] The method consists of using a broadbanded tee, designed by choosing optimum values of the characteristic admittances, and thus forcing the angle of the reflection coefficient to remain small. This, in turn, enables the phase shift associated with the mismatch because of discontinuity to stay below some desired value. This associated phase shift can have serious effects on beam formation and beam position, and greatly influences the side-lobe level.[6]

Tees for use in the full-scale model antenna at 432 Mc/s, having power divisions of 1:1, 1.25:1, and 1.75:1, were designed and built using 1-5/8 inch rigid coaxial line. In all cases, the input VSWR was less than 1.08 over a 15 per cent frequency band. The measured phase shifts, using Keeping's measuring setup and method, were well within the desired design goals. The measured amplitudes at the various outputs changed by less than 0.25 db over the same band-spread. The measured phase shift through a series of tees, as they will be used in the final array, measured less (in some cases) than that of a single tee.

THE DUAL-RIDGE WAVE GUIDE

As an extension of the planar array using ridge wave guide, some preliminary work was done with another form of ridge wave guide, with more than one ridge on the same wall. By the use of a "dual-ridge" wave guide (fig. 16), and the adjacent slot,[2] several radiating systems can be placed in the same aperture dimensions. By proper choice of the spacing between the dual ridges, the spacing of approximately a half-wave required for more than one array in the same aperture is possible. For example, one array can be at a given frequency, and the secondary array can be spaced so that it will radiate at a frequency twice that of the primary array, while maintaining half-wave spacing in both cases (fig. 17). This scheme can obviously be extended to more than two arrays in the aperture dimensions, but with increasing difficulty because of the physical limitations.

The wavelength in the dual-ridge wave guide was measured for a constant-width ridge and for varying heights. Although the quantity of data is limited, it did show that wavelength characteristics similar to those of the single- and double-ridge wave guides can be achieved. For example, the wavelength in the RG-49/U wave guide (1" × 2" O. D.) with an 0.800 × 0.567 inch ridge is approximately the same as that with two 0.250 × 0.700 inch ridges in the same guide. Some wavelengths of various configurations of the dual-ridge wave guide are given in figure 18.

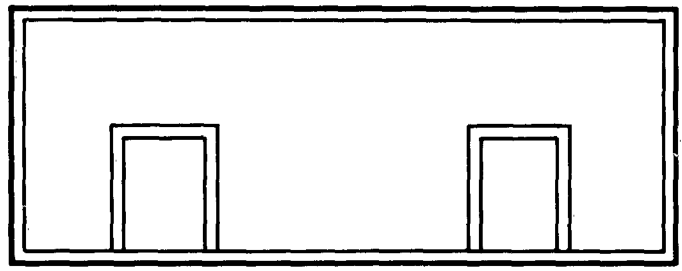

Figure 16. Configuration of dual-ridge wave guide.

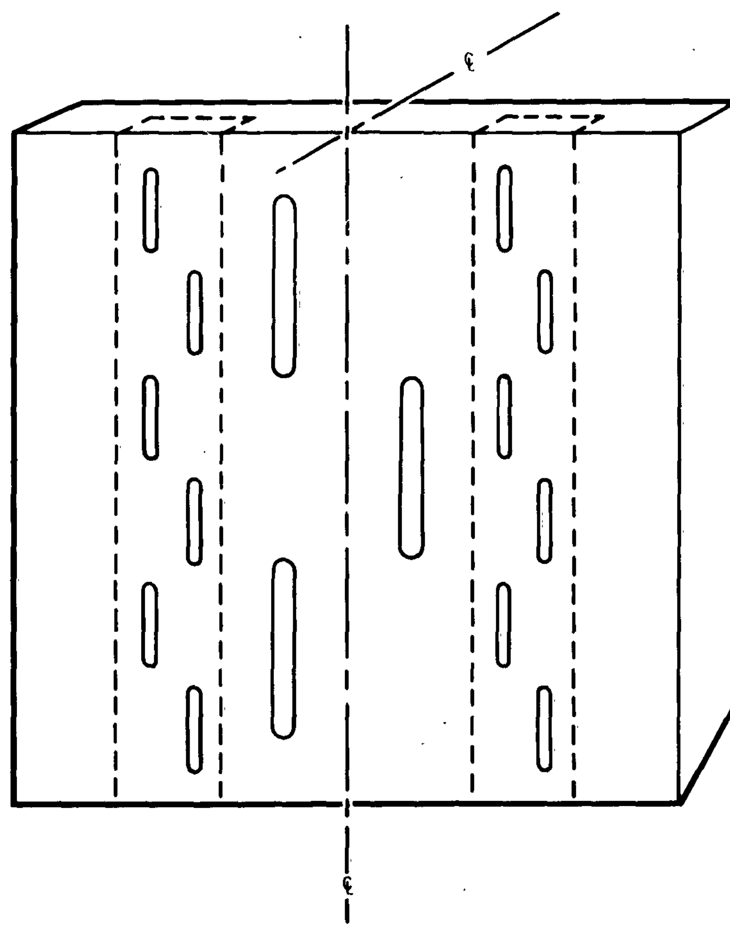

Figure 17. Element of dual-ridge wave guide, showing slot placement.

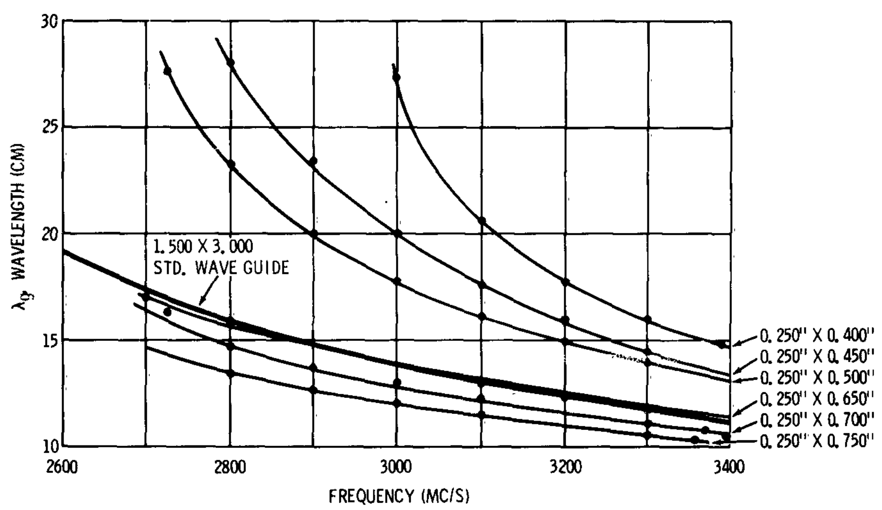

Figure 18. Wavelength of dual-ridge wave guide vs. frequency.

CONCLUSIONS

A scanning array using ridge wave-guide linear arrays as elements has been shown to be capable of scanning through an angle of $\pm 45°$, by the use of a phase-shift method. The radiation patterns of the system for angles near the broadside position are much as expected, although for the angles greater than $\pm 30°$ there is much to be desired. The side-lobe level is somewhat higher than would be predicted, and reflects a variety of errors, both mechanical and electrical. The mutual effects appear to be the largest contributor as the beam is scanned, and a further study of the impedances at these angles would be fruitful. The design of the feed harness by the Keeping method appears to be a solution to the phase dispersion problem, but it was not applied to the S-band models for this work.

A scheme capable of using the given antenna aperture dimensions for multiple-frequency bands by the use of a standard wave guide with two ridges has been proposed.* By proper choice of the ridge dimensions and their spacing within the guide, the half-wave-spaced element requirement for the arrays can be met for two or more independent arrays in the same aperture. This can be simplified if the frequency bands are in approximately even multiples.

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*Invention Disclosure #NC-35, 365, U. S. Navy Electronics Laboratory, San Diego, California, 8 Aug 1962

RECOMMENDATIONS

1. Determine fully the advantages to be gained by the use of a phase-scanned array, when the state of the art produces a low-loss, high-speed, phase-shifting technique.

2. Investigate further the characteristics of the dual-ridge wave guide, with a view to using them as elements in a multifrequency array. This would allow use of the same aperture area for more than one radar (thus providing frequency diversity) or for more than one function, such as in search and guidance.

3. Determine to what extent the frequency band of the fixed-aperture scanning antenna can be extended, utilizing time-delay or variable-path-length beam steering, and broadband tee dividers for amplitude control.

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